NASA Space Transportation Architecture Study

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Introduction

The NASA Space Transportation Architecture Study was established to develop detailed information solicited from U.S. industry to support decisions pertaining to the development of a next generation reusable launch system. NASA requested each of five selected contractors to respond to three specific questions:

"Should the Space Shuttle system be replaced?"

- "If so, when, and how the transition should be implemented?"
- "If not, what is the appropriate upgrade strategy?"

The contractors were also asked to identify the "marginal investment" required by the Government to meet NASA's future human space flight requirements while achieving significant reductions in cost while fulfilling the related goals of the National Space Transportation Policy, which states the Government will:

- "Assure reliable and affordable access to space…"
- "Foster the international competitiveness of the U.S. Commercial Space Transportation Industry…"
- "To the maximum extent feasible, use commercially provided U.S. products and services…"

Space Access, LLC, as the result of its efforts performed under the NASA contract, recommends that the Government establish incentives to serve as a catalyst for commercial finance and promote the development of domestic launch systems which satisfy both the Government and commercial launch service market needs.

In order for the Government to derive maximum benefit from the commercial sector's participation in the development of new launch systems which will benefit both the Government and commercial launch service customers, it is important first to understand the interrelationship between the Government and commercial launch services markets—the common ground between both markets. Although commercial launch services have been "unmanned" to date, the Government's transition towards greater use of commercial launch services will certainly speed up the evolution of "manned" commercial launch systems. Improving reliability is one of the pacing items in this shift from "unmanned" to "manned" commercial launch systems.

Space Access is developing a launch system which is compliant with the FAA's existing Aircraft Airworthiness Criteria, and recommends the Government advance the state of the art in the launch industry by adopting the well-proven FAA airworthiness criteria as its universal standard for procuring launch services. Although none of the current launch systems have been built to such demanding standards, Space Access is developing a new multi-stage reusable launch system that is based on a proprietary breakthrough in air breathing propulsion technology that provides the extra performance required to allow the design to meet all of the FAA airworthiness criteria for transport aircraft. Thus the SPACE ACCESS™ SA-1 launch system has the potential to become the cornerstone of a new era in space transportation.

Space Access, under contract to NASA, has developed a space transportation architecture and recommended implementation strategy which will allow the Government to derive maximum benefit from the commercial development of the SPACE ACCESS™ launch system. The architecture will make future missions involving human on-orbit operations such as next generation space stations, as well as lunar and Mars missions, more economically feasible and on a timetable much sooner than currently planned by reducing launch costs, program risks, and on-orbit assembly time. The recommended approach will enable NASA, within its existing budget guidelines, to achieve its advanced space transportation goals by fostering a space transportation architecture capable of achieving a 10X reduction in launch prices to satisfy launch service requirements for the next decade thereby permitting stable investment in research and development of the technologies necessary to achieve a 100X reduction in launch costs within 20 years.

Interrelationship of Government & Commercial Launch Services

Over 92% of the Government's expenditures for launch services conducted in 1998 (Figure 1) were for the intermediate to heavy spacelift class, including launch vehicles such as Atlas, Titan, and Shuttle. Less than 8% of the Government's launch service expenditures involved light to medium spacelift, such as Delta or smaller launch vehicles. This annual characterization has been consistent for a number of years.

As with the Government market, the expenditures for commercial launch services in 1998 (Figure 2) were also dominated by relatively heavy payloads. Over 74% of the commercial launch market revenues last year were associated with heavy and relatively large commercial GEO payloads and 24% with large commercial LEO payloads, which typically involved deploying multiple LEO satellites. The result is that less than 2% of the total commercial launch services involved relatively small commercial LEO payloads of less than 7,500 pounds.

However, whereas there is considerable common ground in the weight class of payloads being deployed by Government and commercial launch service customers there is no similar common ground with respect to the Government's unique requirement for human access to space. The Government spends 62% of its budget for launch services on human access to space (Figure 3) while there was zero commercial human access to space launch services provided last year.

Hence, if the Government wants to capitalize on commercial developments in the launch system industry, it should focus its efforts on supporting those systems capable of performing medium, intermediate, and heavy lift services, but also capable of supporting the Government's unique need for human access to space capability.

Although commercial launch services have been "unmanned" to date, the Government's transition towards greater use of commercial launch services will certainly speed up the evolution of "manned" commercial launch systems. Improving reliability is one of the pacing items in this shift from "unmanned" to "manned" commercial launch systems.

Manned versus Unmanned Reliability

All domestic commercial launch systems must be licensed by the Federal Aviation Administration (FAA). Since commercial launch systems have typically carried neither a human crew nor passengers, the FAA has concerned itself primarily with protection of third parties not directly associated with ensuring space launch activity. This protection is established through the FAA imposition of "expected casualty" criteria on all commercial launch activity to protect the public. For approval of launch operations to be granted, an operator must demonstrate that less than 30 public casualties would be experienced per million launch missions.

Although the FAA does not regulate Government launch missions, the reliability of Government "Unmanned" Expendable Launch Vehicles is regulated by the Federal Government ranges from which they are launched. To protect the public, the Government ranges impose the same expected casualty criteria as the FAA does on commercial launches: a limit of no more than 30 expected public casualties per million missions.

This expected casualty criteria is currently being met by commercial and Government operators by the establishment of launch flight plans which will ensure that the debris from a catastrophic launch failure will land in a remote, unpopulated area such as the ocean. For new commercial systems to satisfy the Government need for "Human Access to Space" the reliability of the launch vehicles themselves (not just where they may fall) must be increased.

To protect the public, the FAA also requires future manned commercial launch vehicles to comply with the expected casualty criteria. In addition, however, to afford protection for the crew and passengers on-board the system, commercial launch systems which carry humans must also comply with the appropriate Federal Aviation Regulations (FAR) for certifying the airworthiness of aerospace vehicles transporting humans.

Since "manned" vehicles have to be concerned with more than merely "where the debris will fall", the applicable FAA's airworthiness "design criteria" actually specify the required levels of redundancy, including, for example, specific factors of safety on the structure, rather than just the expected casualties per mission.

The Space Shuttle must satisfy both “expected casualty” criteria to protect the public in general, as well as specified “design criteria” to assure vehicle reliability and protect the crew. Applying this combination of constraints has had outstanding results. The Space Shuttle had only one catastrophic incident in over 90 missions to date.

Adoption of FAA Airworthiness Criteria

The FAA Airworthiness Criteria has proven to be an exceptionally effective method of increasing reliability and decreasing costs, and thus assuring safe transport of passengers and crews for the commercial aviation industry. In 1998, operating under the Federal Aviation Regulations, U.S. Air Carriers generated over $83 billion in revenues while experiencing not a single catastrophic loss or fatality.

The FAA airworthiness criteria prescribe factors of safety and levels of aircraft system redundancy to account for unknowns, including considerations such as the accuracy of the system design and analyses, extent of material characterization, the uncertainty in actual system operating environment, and variations in the manufacturing processes. Extensive flight envelope expansion programs are required in conjunction with robust factors of safety to assure the accuracy of design based predictions.

The FAA’s airworthiness criteria specify minimum acceptable practices on virtually all aspects of the design, production, and operation of aerospace vehicles. As an example, factors of safety (Figure 4) are specified to assure structural redundancy and reliability. The ultimate strength of even the most well characterized materials are divided by a conservative factor of safety to determine the “limit” stress load for each material. The developer must design to assure no material exceeds its limit, and then show in a flight envelope expansion program that the loads were indeed predicted accurately. If not, then restrictions are put on the operation to avoid exceeding the limit.

The factors of safety specified by the FAA are dependent upon whether or not the structure is pressurized. The pressurized cabin of an aircraft as well as the pressurized propellant tanks of a launch system, for example, are required to have a much more conservative factor of safety (2.0) than a non-pressurized structural element such as the vertical tail of an aircraft (1.5).

Since the FAA and the Federal Government ranges impose “expected casualty” rather than “design criteria” on expendable launch vehicles, the factors of safety used are typically much less and vary from 1.1 to 1.2 for both pressurized and unpressurized structures. In other words, there is less than 20% redundancy in the structure. Because of this minimal margin for error, minor perturbations during a mission caused by even momentary failures of systems, such as the guidance and control, can easily result in catastrophic failure of the vehicle structure.

Although the Space Shuttle as a Government program is not subjected to FAA regulation, it was primarily designed to factors of safety ranging from 1.4 to 1.8 for unpressurized and pressurized structure, respectively. However, numerous exceptions do exist in which factors of safety of less than 1.2 are being used, including the restraining hardware which hold the Space Shuttle in place on the pad prior to lift-off.

The FARs governing airworthiness (e.g., FAR Part 25 Transport Aircraft Airworthiness Design Criteria) have served as the foundation upon which the U.S. air carriers have built one of the world's safest and most reliable industries. Over the past four decades, no similar trend is evident for the domestic expendable launch vehicles (ELVs) which have operated solely under expected casualty criteria. The average number of missions between catastrophic failures (Figure 5) of major domestic ELV's (Delta, Atlas, Titan) shows no improvement, and continues to linger between ten and fifteen. Although the expected casualty criteria has served well to protect the innocent public, it apparently has not served as a foundation for building mission reliability.

The Space Shuttle, upon which NASA imposed design criteria in many ways similar but somewhat less conservative than FAA standards, has on the other hand demonstrated a significant trend towards more reliable mission operations, approaching an order of magnitude improvement in reliability compared to ELV's. This infers that the more conservative design criteria used on the Shuttle have allowed the system (and crew!) to survive on occasions where minor perturbations might otherwise have caused catastrophic failure.

Since the environment in which launch systems operate is even more challenging than the environment to which transport aircraft are typically exposed, it would seem prudent to incorporate airworthiness design criteria for new launch systems to, as a minimum, achieve the phenomenal reliability record currently enjoyed by the Space Shuttle and, ultimately, advance toward that of commercial aircraft.

Increasing the reliability of launch systems has significant benefits besides enhancing the safety of the passengers and crew. The benefits of increased reliability can also be defined in the relationship between revenue generated by providing services versus the financial losses associated with catastrophic failures. Applying this financial definition of reliability (Figure 6), the phenomenal reliability of the U.S. domestic air carriers is dramatically illustrated.

This relationship is illustrated in the accompanying figure by the amount of expenditures in 1998 for various categories of transportation services as compared to the losses associated with the delivery of those transportation services—as measured on a logarithmic scale in millions of dollars. The U.S. commercial air carriers generated over $83 billion in revenue and incurred zero losses as a result of catastrophic incidents. In contrast, the U.S. commercial launch services providers generated $922 million in revenue but incurred $248 million worth of losses associated with the delivery of those launch services. Those losses represent 27% of the total commercial launch services revenues. Similarly, the U.S. Government required $1.48 billion worth of expendable launch vehicles (ELVs) spacelift services while incurring an astounding $1.36 billion of related losses, which equates to 92% of the expenditures on the spacelift services. It is clear that both the Government and commercial launch service customers could benefit significantly from increasing the reliability of the launch services they use.

It is apparent that increasing launch system reliability, which is necessary to accommodate safety requirements associated with human access to space, is also necessary to achieve significant reductions in the cost of access to space. Thus, it will benefit not only customers for "manned" launch services but “unmanned” spacelift customers as well. Based on the success experienced by U.S. Air Carriers, significant improvements in reliability and the associated benefits from reductions in losses due to catastrophic failures are indeed worth pursuing.

SPACE ACCESS™ Reusable Launch System

Space Access, LLC is developing a multi-stage, fully-reusable, air-breathing launch system which has the potential to revolutionize the world’s access to space. Under the NASA Space Transportation Architecture Study, Space Access has identified a variant of the SPACE ACCESS™ commercial launch system which provides access to space for the complete spectrum of payloads from Humans and Human-Related Cargo through Non-Human Related Cargo. Both the commercial system and the variant for NASA are designed in compliance with both FAR Part 25 (Commercial Transport Aircraft) and FAA Guidance for licensing Commercial Launch Vehicles.

The SPACE ACCESS™ launch system for NASA has extensive commonality with the SPACE ACCESS™ commercial satellite launch system. The launch system accommodates all NASA International Space Station up and downmass requirements, including the transfer of crew and passengers (up to five) and the transfer of the same payload transfer modules planned for use on the Space Shuttle: the Multipurpose Logistics Module (MPLM) for pressurized cargo and Unpressurized Cargo Pallets for unpressurized cargo.

The characteristics of the SPACE ACCESS™ launch system make it well suited for NASA missions: cost effective, reliable, responsive, and, is commercially developed and operated thus achieving the goals of the National Space Transportation Policy. By more cost effectively satisfying both commercial and Government needs, it facilitates the Government’s transition to greater use of “commercial” launch services, saves the Government billions of dollars annually, and, invigorates the U.S. commercial space industry’s competitiveness.

A proprietary, high-performance, ejector ramjet propulsion system propels the first stage of the SPACE ACCESS™ launch system while within the atmosphere, and is the key enabling technology of the multi-stage launch system. The highly efficient air-breathing engines minimize the weight of the propellant that must be carried. As a result, instead of the burden of carrying large amounts of propellants, weight is allocated to carry the provisions necessary to comply with FAR Part 25. In addition, provisions used heretofore only in aircraft are incorporated to enhance producibility and maintainability, allowing more cost effective production and operation. Furthermore, the launch system accommodates all classes of commercial and Government payloads, including heavy-lift and human access to space.

The baseline commercial SPACE ACCESS™ launch system is designed to be capable of deploying the largest next-generation geosynchronous satellites into Geosynchronous Transfer Orbit (GTO). This mission is accomplished using three autonomous, fully-reusable stages. The first stage takes off horizontally from a runway powered by highly efficient ejector ramjet engines. After accelerating to hypersonic speeds within the atmosphere, the first stage climbs up out of the atmosphere and deploys the second and third stages together with their satellite payload. The second stage spacecraft, powered by a conventional rocket engine, accelerates into Low Earth Orbit (LEO) where it deploys the third stage and satellite payload. The third stage, also powered by a conventional rocket engine, then positions the satellite in Geosynchronous Transfer Orbit. As their missions are completed, each of the three reusable stages returns to land horizontally at the original deployment site. Militarized versions of the upper stages increase the payload significantly so that the system can accommodate any Geosynchronous payload currently deployed by Titan IV.

The same commercial, fully-reusable first and second stages can be used to very efficiently deploy payloads to LEO (Figure 7). As a fallout of designing for the most demanding commercial GTO mission, up to 35,000 pounds of payload can be deployed to LEO by the fully reusable system. Again, the use of a militarized second stage can increase the capacity to accommodate any Titan IV class LEO payload. Ample volume has been provided in the payload bay to assure that the fully reusable launch system can be used interchangeably with any current or proposed expendable launch system including the Titan IV.

The SPACE ACCESS™ fully-reusable launch system is also capable of carrying Human-Related Cargo to the International Space Station (ISS). The only modification to the basic commercial second stage is the addition of an on-orbit maneuvering pack to provide the additional attitude control system redundancy and full translation capability necessary to rendezvous and dock with the ISS. The Human-Related payload capacity up to Space Station orbit is interchangeable with that of the Space Shuttle—a full standard Multi-Purpose Logistics Module (MPLM) can be deployed (Figure 8).

The SPACE ACCESS™ system is designed to accommodate crew transfer (up or down) and payload down mass requirements, through the use of a vehicle designated the SPACE ACCESS™ Shuttle (SAS) (Figure 9). The SAS, used in conjunction with the commercial first stage, can transfer up to five crew members or passengers to or from the ISS. On the return mission, the SAS can accommodate a crew and fully loaded MPLM. In addition, the SAS is capable of conducting on-orbit operations (Figure 10). The SAS is essentially a “stretched” version of the commercial second stage, with a crew compartment and a payload bay large enough for the MPLM added. Like the first stage, the SAS is also designed in compliance with FAR Part 25 Airworthiness criteria for Transport Aircraft, in order to be licensed for the commercial transport of crew and passengers for hire.

The Space Shuttle is unique in that it is currently the only vehicle with a payload bay capable of transporting the MPLM full of racks of experiments (including space manufactured commercial products) from the ISS back to Earth. Space Access considered crew transfer vehicles, derived from the Crew Return Vehicle, as an alternative to the SAS. The conclusion was that the utility of such a vehicle was limited due to the small cargo downmass and limited on-orbit operations capability which precluded interchangeability with the Space Shuttle. A MPLM (or similar carrier such as the SpaceHab logistics module) downmass capability is necessary to assure the experiments conducted, and commercial products manufactured aboard the ISS, could be returned to Earth. On-orbit operations are required to maintain systems such as the Hubble Space telescope and construct the next generation space station. Hence, it was concluded that MPLM downmass capability and on-orbit operations capability were essential features of any true Space Shuttle replacement. Thus the use of the SAS, in conjunction with the SPACE ACCESS™ commercial launch system, together capable of accommodating both up and downmass, was found to be much more efficient and cost effective than the use of a dedicated crew transfer vehicle.

Validation of Enabling Technologies

The performance advantage afforded by the efficient air breathing ejector ramjet propulsion system and vehicle staging permit a conservative design approach. In addition to aircraft factors of safety, structural weight and performance margins are incorporated in the SPACE ACCESS™ launch system. Data used in the design is based on the demonstrated performance of commercial off the shelf components and experimental test.

To date, an extensive series of wind tunnel tests have been conducted in three separate facilities spanning the flight envelope. These tests, together with computational analyses, have been used to validate the aeromechanics and optimize the aero-propulsive performance of the system configuration. Lower speed wind tunnel tests were accomplished for Space Access by Northrop Grumman Corporation in their wind tunnels located in Hawthorne, California. Hypersonic wind tunnel tests (Figure 11) conducted at the USAF Arnold Engineering and Development Center in Tullahoma, Tennessee, validated the high speed aeromechanics.

A third-scale ejector ramjet was constructed (Figure 12) and ejector ramjet testing conducted (Figure 13) at the Kaiser Marquardt facility in Van Nuys, California validating the ejector ramjet performance. An existing ramjet that had been tested from Mach 3 to 8 was modified to incorporate a proprietary system of ejectors in the inlet duct, allowing the ramjet to operate very efficiently at low speeds.

Recommended Implementation Strategy for NASA

The SPACE ACCESS™ launch system is capable of fulfilling all of the Space Shuttle mission requirements and achieving NASA's goal of reducing current launch costs by a factor of ten within ten years and thus offers the potential of saving the Government over $40 billion through 2020 while simultaneously advancing the standards of launch system reliability—all through a commercially developed and operated system.

Space Access recommends the Government provide incentives in the form of advanced purchase launch agreements to replace shuttle flights thereby promoting the commercial development of multiple launch systems that benefit both the Government and commercial sectors.

The Government should use contractor compliance with FAA airworthiness design criteria (e.g., FAR Part 25 for transport aircraft) as a benchmark upon which to provide the incentives.

The Government incentives would be based upon the appropriation of funds within the NASA FY99 budget (e.g., $150M in FY01 and $300M annually thereafter). NASA's funds would be preceded by substantial commercial investment; and, contingent upon successful completion of mutually agreed program performance and commercial finance milestones. The incentive program would be structured to cultivate new competition every two years.

The use of Government incentives will serve as the catalyst to promote the commercial development of launch systems that offer the greatest potential benefits to both the Government and commercial launch customers. That "common ground" includes the capability to accommodate medium to heavy payloads; the potential to satisfy NASA's ten year goal of reducing launch costs 10x; and, compliance with FAA launch vehicle licensing criteria as well as the FAA's airworthiness criteria for commercial operation of vehicles carrying crew and passengers for hire.

Space Access recommends NASA enter a commercial launch service agreement contract with Space Access through an incentive program structured to promote commercial investment in new launch systems, advance the state of the art in launch system reliability, and reduce the cost of Government space launch. The incentives can be accommodated within the existing NASA FY99 budget and would serve as the "vote of confidence" necessary to energize the private sector investors to provide the financing required for new launch systems. NASA would benefit from reduced launch service costs resulting from competing, commercially operated, highly reliable, and efficient reusable launch systems. NASA would no longer pay for the development and operation of launch vehicles. Space Access will pay for the use of NASA resources and facilities (e.g., Aerodynamics, Thermodynamic, Propulsion, Structures, etc.) throughout the program. NASA should continue, in parallel, to fund "technology development" programs to mature the technology that will serve as the basis for next generation RLV's capable of even greater reductions in launch costs such as the much more difficult goal of a 100x reduction in launch costs within twenty years. The savings generated by NASA's use of the SPACE ACCESS™ launch system will allow NASA to focus more of its limited budget on discovery and exploration of space.